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Title: FIELD- AND RESONANCE-CONTROL MODULE (155Y503002) OVERVIEW

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Field/Resonance Control Module

The Field/Resonance Control Module (FRCM) continuously monitors the cavity field amplitude and phase, and the actual cavity resonant frequency. The field-control portion of the module minimizes deviations of the cavity field amplitude and phase from their respective set points and compensates for the field perturbations caused by the beam. The resonance-control portion of the module calculates the difference between the cavity design frequency (402.5 MHz or 805.0 MHz) and the actual cavity resonance frequency. It then outputs the error to the Experimental Physics and Industrial Control System (EPICS). EPICS forwards this frequency error (in Hertz) to the appropriate cavity-tuner system. Both of these functions are accomplished by adjusting the frequency, phase, and amplitude of the RF carrier supplied to the high-power transmitters; however, although they are interrelated, they are distinct functions. This section describes both the control strategies and the hardware approach to meet these requirements.

The SNS FRCM uses digital feedback- and feedforward-controls to regulate the field parameters of an RF cavity of the SNS linac. The FRCM performs feedback- and feedforward-control algorithms on the field intermediate frequency (IF), resulting in baseband-control in-phase and quadrature (I/Q) outputs, which are then upconverted to the appropriate carrier frequency prior to amplification by the klystron.

The FRCM uses two on-board Texas Instruments TMS320C6203B digital signal processors (DSPs). The DSPs provide the intelligence for controlling most of the functions of the FRCM, including the digital beam feedforward loop, resonance control and monitoring, fault monitoring, supervisory control of the analog functionality, and the VXIbus-interface function. The digital field feedback function is performed in a complex programmable logic device (CPLD).

The fault-monitoring function of the FRCM consists of turning off the RF power in response to an external fault and initiating a fault if the PID controller saturates, a quench is detected (for superconducting RF—SRF—cavities only), or the FRCM built-in test (BIT) logic detects a module fault. The BIT error's fault responses are programmable through EPICS and DSP interfaces.

The control of the FRCM is accomplished though the shared-memory A24 VXIbus interface with EPICS. The control parameters are set through the EPICS interface, and the DSPs provide the direct interface to the control register and hardware.

Field Control

The FRCM maintains the cavity field at the specified magnitude and phase during normal operations by sampling the cavity field and comparing the result against a desired set point set via EPICS.

All processing is done on the I and Q set points of the field, but for common understanding by the users, the description of the field set points is always done in amplitude and phase. EPICS immediately translates these amplitude and phase set point inputs on the screen to I and Q set points.

Two controllers are involved in the field-control strategy. The first controller is the proportional-integral-differential (PID) feedback controller, which maintains the field amplitude and phase in relation to the specified set point. This feedback controller will respond to all transient and periodic disturbances and requires a control bandwidth wider than the cavity bandwidth.

The second controller in the system is the feedforward controller, which suppresses repetitive disturbance, such as power-supply ripple and beam-loading, by estimating these errors from past data and applying a corrective signal. The implementation of the feedforward controller is an error-adaptive feedforward controller known as an iterative-learning controller. An optional beam feedforward controller will be accommodated in the hardware, but will not be implemented initially. For more details, see Technical Note LANSCE-5-TN-00-014.[1]

Field-Control Design and Modeling

The control algorithms for the various normal-conducting (NC) and SRF cavities have been designed and modeled to assure precise control of the cavity field in compliance with the requirements. We use a state-space modeling program (MATLAB/Simulink) that provides linear and nonlinear functions, common signal-processing and control functions, spectral stimulus/response, and modern control utilities for mixed continuous- and discrete-time analysis to develop and prove out the control algorithms.

The objectives of the modeling effort are to

- develop performance specifications for RF components and subsystems,
- validate the system design and performance objectives,
- optimize the control parameters and algorithms,
- simulate the RF system under normal and transient conditions, and
- create a mathematical test bed for exploratory control-system development.

Resonance Control

In addition to field control, the purpose of the FRCM is to control the resonant frequency of the accelerator cavities to maximize the RF power transfer from the klystrons to the cavities. To do this, the FRCM determines the actual resonant frequency of the cavity using

1. Kwon, S.I., Y.M. Wang, and A. H. Regan, "SNS Superconducting Cavity Modeling—Iterative Learning Control," Los Alamos National Laboratory Technical Note LANSCE-5-TN-00-014 (LA-UR-00-4372), 2000.

algorithms that determine the resonance frequency based on cavity field, forward, and reflected power. Different algorithms are necessary for NC and SRF cavities. The NC cavity resonance frequency is calculated from the imaginary portion of the load admittance. The SRF cavity resonance frequency is calculated from the time response of the cavity.

The method/algorithm from which the FRCM calculates the NC cavity's resonant frequency is detailed in Technical Note AOT-5-TN:008.[2] Essentially, it calculates the cavity's admittance based on the forward and transmitted RF signals. The imaginary part of the admittance, Im(YC), is linear to the error of the resonant frequency of the cavity. The DSP within the FRCM performs the following calculation, where the subscript C indicates cavity, T indicates transmitted, and F indicates forward:

$$Im(Y_C)=0.2\ [I_T.Q_F-I_F.Q_T]/[(I_F+I_R)^2 + (Q_F+Q_R)^2]$$

The DSP calculates the frequency error and outputs the result to EPICS.

NC Resonance-Control Example

When cold, the cavities are designed to be slightly (a few hundred kHz) above their design frequency. With the application of RF power, they heat up and expand, and their resonant frequency drops to the design point. If the RF is driven at the design frequency and the cavity is far off-resonance (as during a cold start), the cavity will reflect most of the RF power supplied to it. Under these conditions, measure the cavity's actual resonant frequency and adjust the RF drive frequency to match. This will maximize the RF power into the cavity, heating it up and lowering its resonant frequency to the design value. This is the "Frequency-Agile Mode" (see Figure 1).

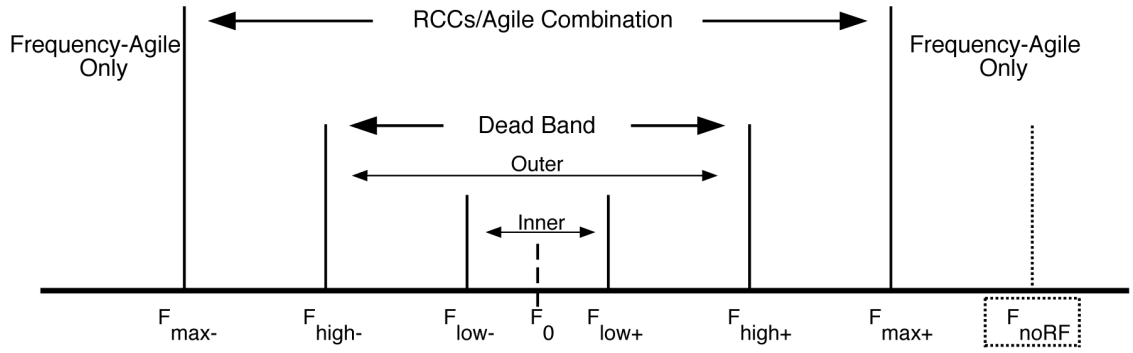
Under normal operations, the typical turn-on scenario consists of turning on the klystron beam voltages, then raising the cavity field set point to the nominal value and closing the field-control loop. The field-control loop operates in I/Q-Control Mode while in the Frequency-Agile Mode. Once the frequency is correct, lock the output to the master oscillator and switch to Field-Control Mode.

Field-Control Mode occurs when the resonant frequency of the cavity is close enough to the cavity's design frequency that the water-cooling Resonant-Cavity-Control System (RCCS) can control the cavity's resonance frequency by itself. Within this dead band, the FRCM locks to the design frequency and lets the RCCS control the cavity temperature (and hence, cavity center frequency) to keep it centered at the design value. If the cavity resonant frequency moves too far off-center (F_{high}), the beam turns off, and Frequency-Agile Mode is activated

2. Regan, A.H., "LLRF Technical Note on Resonance-Control Algorithms," Los Alamos National Laboratory Technical Note AOT-5-TN:008 (LA-UR-00-5074), 2000.

The (F_{noRF}), reference, in Figure 1, to 140 kHz is cavity-specific for the coupled-cavity linac (CCL) and the CCL Hot Model. The various frequency points specified in the figure are adjustable via EPICS. Hysteresis is implemented by specifying different cut-in (flow) and cut-out (high) frequencies to prevent chatter at the resonance- and frequency-control boundary. Communication of the error frequency between the RFCS and the RCCS is accomplished through EPICS.

Figure 1. Frequency-Agile Resonance Control



F_0	design-resonance frequency
F_{low}	frequency-agile-to-field-control transition frequency
F_{high}	field-control-to-frequency-agile transition frequency
F_{max}	maximum RCCS control frequency
F_{noRF}	cold cavity frequency

SRF Resonance-Control Example

On a cold start, the RFCS must locate the resonant frequency of the SRF cavity and force it to the design point of 805 MHz. It does this in a two-pass algorithm of coarse- and fine-frequency steps by using the Frequency-Agile drive capability of the FRCM. The algorithm starts a number of cavity bandwidths below the 805-MHz design frequency, and drives the cavity with approximately 2 s of RF pulses at the 60-Hz pulse-repetition rate. The FRCM then increases the drive frequency by 1 kHz, and repeats the process. By continuously monitoring the resulting cavity field amplitude, the FRCM can determine the coarse resonant frequency based on the cavity response—the cavity field amplitude will peak near the resonant frequency.

The fine-tune for the SRF cavities relies on beam excitation of the RF cavity followed by measuring the cavity field decay time response. See Lloyd Young's paper for details.[3]

Once the actual cavity resonant frequency is found, the FRCM will send the *error frequency* to the cavity tuner via EPICS to bring the cavity to exactly 805 MHz. Software (provided by the LANL Global Controls Group, SNS-4) will map the EPICS error signal from the FRCM to actual motor-drive commands. During operations, the FRCM will continue to monitor the cavity resonant frequency and send an error signal to the cavity tuner, as needed. Given the reputed stability of SRF cavities, this should occur relatively infrequently.

Note on phase error in Frequency-Agile Mode (Revision C and earlier versions only:

The technique used for I/Q downconversion in the SNS FRCM relies on the coherency of the IF and analog-to-digital converter (ADC) sampling clock. In Rev. C and earlier versions, these two signals are not coherent in Frequency-Agile Mode (either NC Resonance-Control or SRF Sweep Mode.) This incoherency results in I and Q samples having a non-orthogonal relationship. The maximum deviation from the orthogonal is less than one degree at the maximum frequency excursion. This condition results in an amplitude modulation on the baseband I/Q signal. Because of the way we process the data, and also because we are only trying to maintain constant field amplitude during the Frequency-Agile Mode, this condition should not impact the performance of the system.

Rev. D resolves this problem by deriving the ADC sampling clock from the DDS output, resulting in a coherent system.

FRCM Architecture

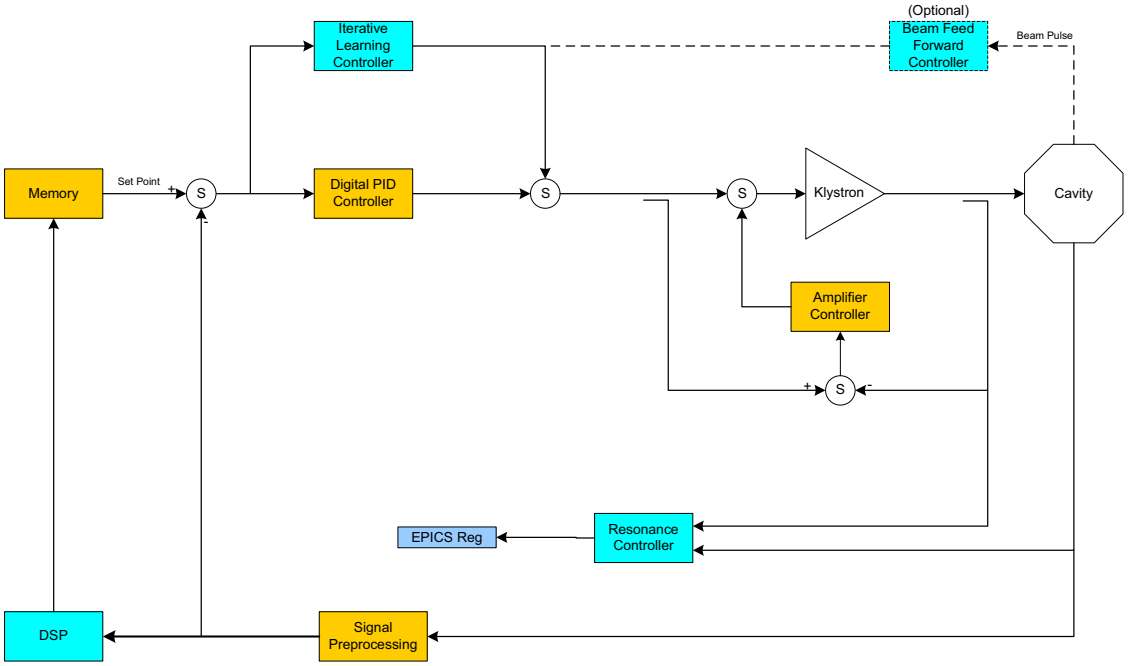
Figure 2 shows a simplified functional block diagram of the FRCM and its four major functional blocks. The four blocks consist of the following:

1. The fast digital PID controller in the main feedback-control loop.
2. The amplifier controller, which regulates the klystron output to a desired magnitude and phase determined by the main PID feedback controller. The amplifier controller's bandwidth will be at least one order of magnitude below that of the main feedback controller to prevent instability caused by the unwanted interaction between the two controllers.
3. The iterative-learning feedforward controller, which reduces repetitive noise and improves transient response to periodic disturbances.
4. The resonance controller, which provides an error signal to maintain the RF cavity at the desired resonance frequency during normal operation and which follows the NC RF cavity resonance in the Frequency-Agile Mode during power-up and conditioning.

3. Lloyd, L.M., "A Procedure to Set Phase and Amplitude of the RF in the SNS Linac's Superconducting Cavities," Los Alamos National Laboratory (LA-UR-01-3142), 2001

During power-up of the SRF cavities, this functional block identifies the correct resonant frequency of the cavity and provides a tuner-motor correction signal via EPICS.

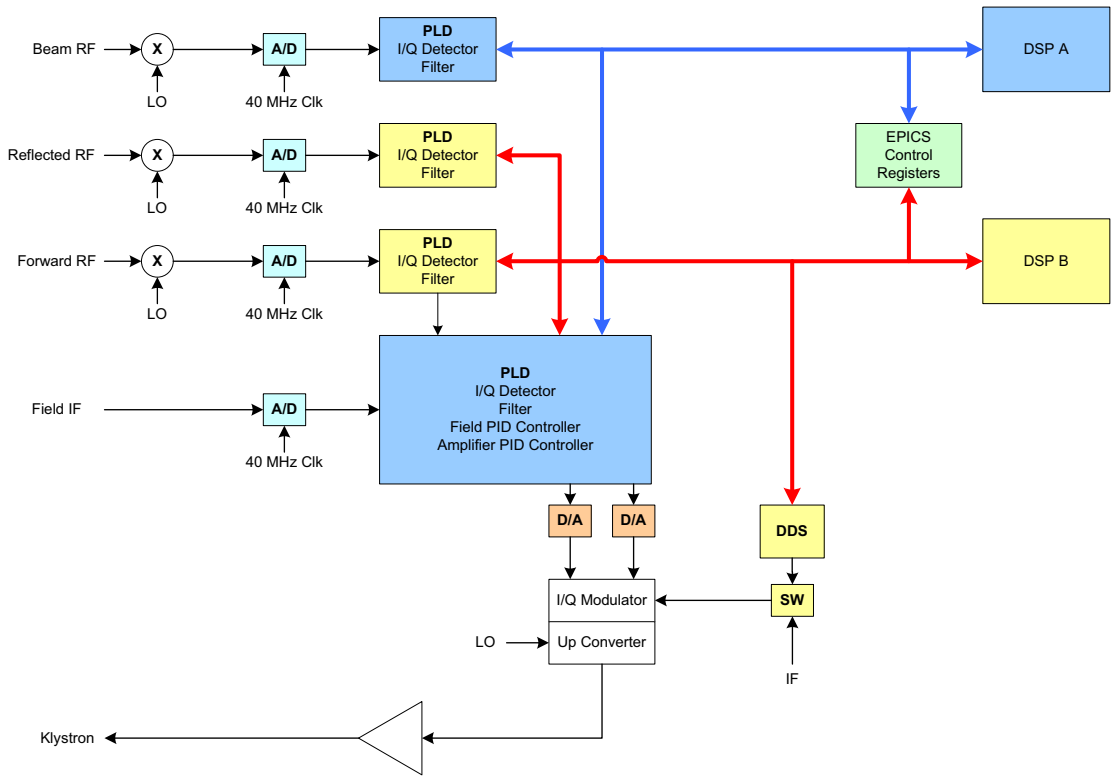
Figure 2. FRCM Top-Level Functional Block Diagram



FRCM Hybrid CPLD/DSP Architecture

The control algorithms are implemented by a hybrid CPLD/DSP-based architecture in which the fast critical path signal is processed with CPLD technology for fastest throughput and minimum latency. The feedforward and resonance-control algorithms are processed through the DSPs to take full advantage of the computational power of their advanced DSP technologies. The signal-flow diagram is shown in Figure 3.

Figure 3. Signal-Flow Diagram of the FRCM



FRCM Physical Configuration

The FRCM uses a motherboard/daughterboard hardware architecture with three plug-in-board slots, two for the DSP boards and one for the front-end RF boards. Figures 4 and 5 show the FRCM motherboard's physical layout. The motherboard provides the interfaces to the RF and DSP modules, along with signal-processing and diagnostic functions. The detailed module input/output (I/O) interface may be found in secton **FRCM Signal I/O**.

Figure 4. Physical Layout of the FRCM Motherboard (top)

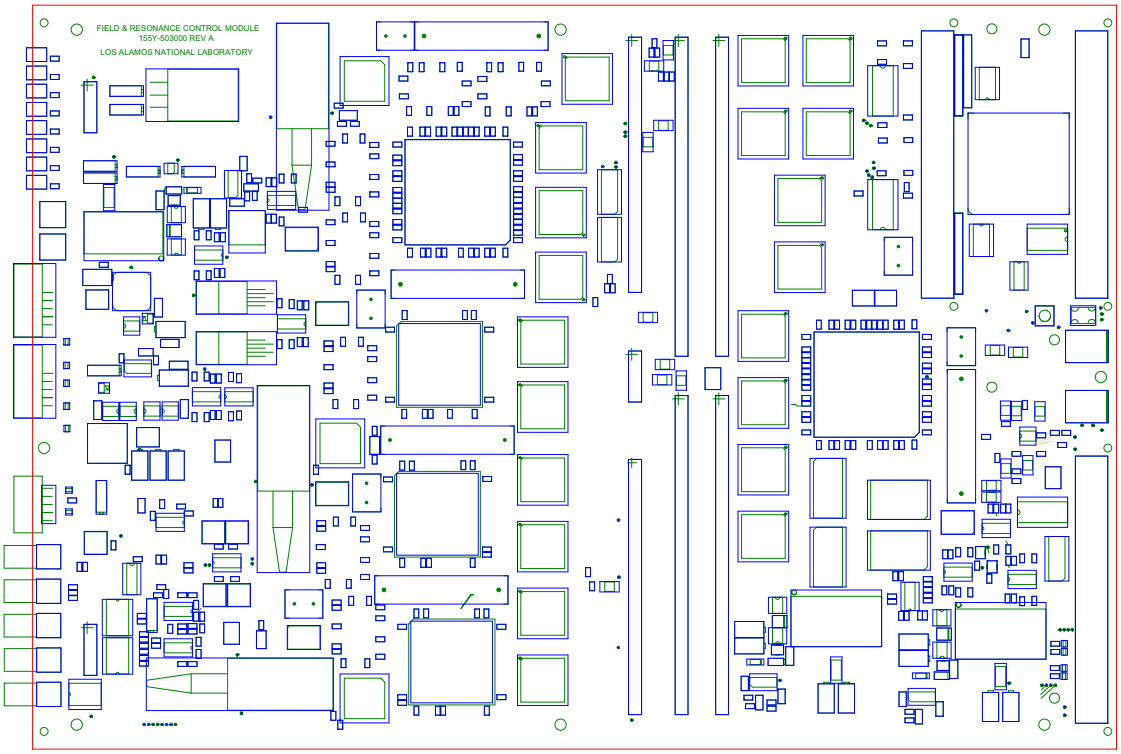
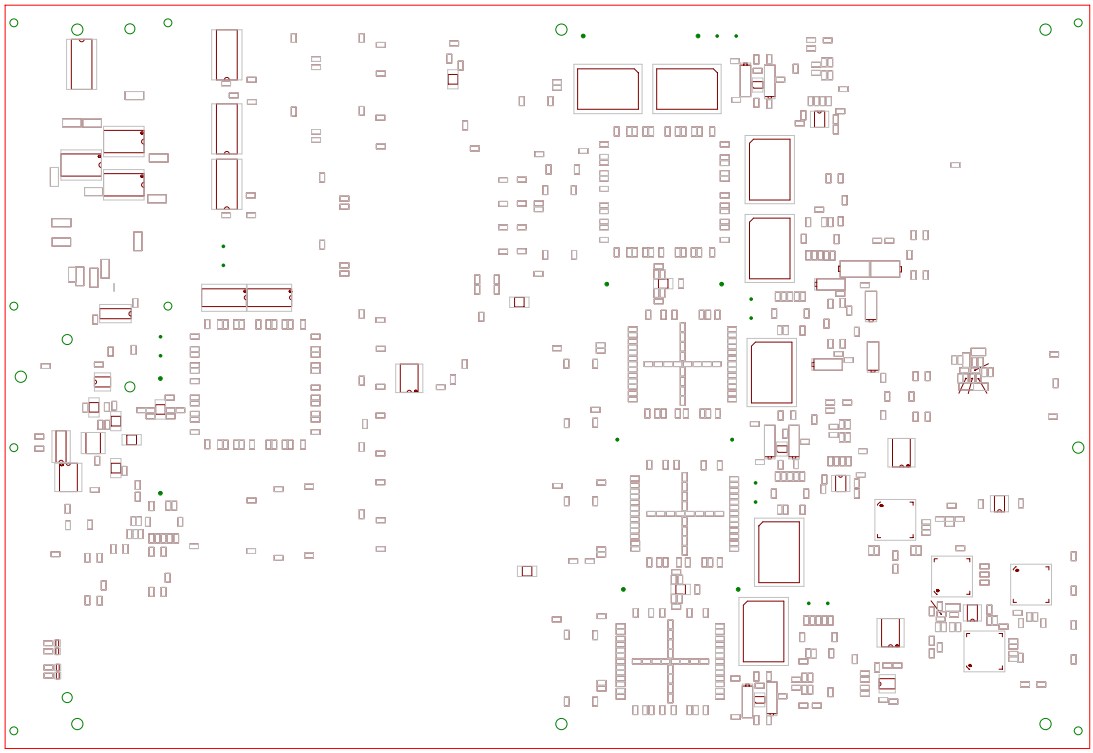


Figure 5. Physical Layout of the FRCM Motherboard (bottom)



FRCM Functions

Modes of Operation

The FRCM will be able to manage up to eight different pulse-to-pulse modes that will be defined by SNS operational requirements (e.g., different targets, pulse widths, etc.). Note that the FRCM needs to know (via EPICS) that the previous pulse was defective or aborted so that the adaptive algorithms can reject the pulse.

FRCM Diagnostics

FRCM diagnostics for accelerator operations are provided via EPICS and over dedicated fiber-optic data links to the control room. Real-time field I and Q data for each cavity will be provided to the control room via fiber-optic data links, with any two of the cavity fields selectable for display. The receivers for FRCM data links for the entire linac require about 2 ft of 19-in. rack space in the control room, plus room for the oscilloscope to display the

data. Phase and magnitude, or I/Q data, are available for each cavity. Filtering of the raw signals is accomplished by the control room electronics.

RF Channel Monitors

All RF and IF I/O channels have integral detector diodes for monitoring power levels. These are readable through EPICS.

Pulse-Quality Monitoring

The pulse quality is monitored and used for updating the feedforward algorithms. The integrated power (pulse energy) is calculated for each pulse and compared to the expected value; when a pulse falls outside of the nominal bounds, the adaptive algorithms ignore the resulting data.

History Buffers

History buffers provide access to FRCM diagnostic data through EPICS. The following five history buffers are available:

- Beam
- Reflected
- Forward
- Cavity (History Buffers 1 and 2)
  - Cavity Field
  - Cavity Error
  - Uncorrected Cavity Out
  - Amp Error
  - Amp Out
  - Cavity Out

Any two of the six cavity history buffers are available simultaneously. Each history buffer continuously accepts data and stops filling on the trigger event. The buffer length is 32K words/channel, which results in a buffer length of 1.64 ms (50 ns/sample). The history buffer data has an associated decimation factor (1x—256 x) to reduce data load on EPICS. This factor is EPICS-programmable through the EPICS interface.

Trigger Events

1. Fault (default): Derived from TTLTRG bus.
2. Data/Threshold: Programmable limit for data path.
3. Synchronous trigger with next pulse
4. Sample pulse

Trigger Types

1. Single Shot (default).
2. Continuous.

Calibration

Each module will be calibrated prior to use to compensate for module-to-module variations in amplitude and phase response and to insure that all modules are interchangeable. This calibration corrects for module set points, component tolerances, and DC offset. In-situ calibration of the module will provide the capability to add interpulse test and calibration. These features are either automatic or on-demand.

Built-in Self-Test

The built-in self-test capability allows off-line independent testing to determine the full functionality of the module and its components.

FRCM Signal I/O

General Specifications

Digital I/Q Control

Channel Numbers	3
Dynamic Range	60 dB
Measurement Resolution	0.01%/0.01^{o}
Measurement Accuracy	0.1%/0.1^{o}
Measurement Bandwidth	1 MHz
Control Bandwidth	> 200 kHz
Digital History Buffers	8x32K words

Resonance Control

Maximum Control Bandwidth	375 kHz
Measured Frequency Accuracy	< 10 Hz
Measured Frequency Resolution	< 1 Hz
Measurement Resolution	0.01%/0.01^{o}
Measurement Bandwidth	1 MHz
Digital History Buffers	4x32K words

Other Functionality

Stimulus/Response characterization of control functions

FRCM Interface I/O

Inputs	Signal Level	Frequency	Connector
BEAM	<10 dBm into 50 Ω	RF	PKZ
CAV_FLD	<10 dBm into 50 Ω	IF	PKZ
REF_FLD	<10 dBm into 50 Ω	RF	PKZ
FWD_FLD	<10 dBm into 50 Ω	RF	PKZ
LO	+24 dBm into 50 Ω	RF - 50 MHz	PKZ
IF	<10 dBm into 50 Ω	50 MHz	PKZ

Outputs	Signal Level	Frequency	Connector
RF_OUT	+ 12 dBm with 50 Ω	RF	PKZ

Test Points	Signal Level	Frequency	Connector
I	-1V to +1V into 50 Ω	DC – 5 MHz	LEMO-1
Q	-1V to +1V into 50 Ω	DC – 5 MHz	LEMO-2

LED Indicators	"On" Function	Color
MODSEL	VXIbus Address of Module	Yellow
FRCM FLT	Control Fault	Red
RF FLT	RF Fault	Red
BEAM	Over/Under Range	Red
CAVITY	Over/Under Range	Red
FORWARD	Over/Under Range	Red
REFLECTED	Over/Under Range	Red
OUTPUT	Over/Under Range	Red

JTAG Headers	Function
PLD JTAG	PLD Interface/Programming
DSP JTAG	DSP Interface/Programming

Trigger Inputs	Functionality When Driven	Backplane
40MHz	ADC Sampling Clock	ECLTRG00
SYNCH	I/Q Synchronization Pulse	ECLTRG01
SAMPLE*	Sample I/Q Data	TTLTRG0*
RF_PERMIT_C	RF Fault (Center)	TTLTRG2*
RF_GATE*	RF Gate signal from the CDM	TTLTRG3*
PREPULSE*	Pulse timing fiducial	TTLTRG4*
RF_PERMIT_L	RF Fault (Left)	TTLTRG5*
RF_PERMIT_R	RF Fault (Right)	TTLTRG7*

Trigger Ouputs	Functionality When Driven	Backplane
SRF_TUNE	Inhibits RF Faults during SRF Tuning	TTLTRG1*
RF_PERMIT_C	RF Shutdown Fault (Center)	TTLTRG2*
RF_PERMIT_L	RF Shutdown Fault (Left)	TTLTRG5*
BEAM_PERMIT	RFCS not ready for beam	TTLTRG6*
RF_PERMIT_R	RF Shutdown Fault (Right)	TTLTRG7*

FRCM VXIbus Interface

Configuration Registers	Value	Bits
DEVICE CLASS	Extended	01_2
ADDRESS SPACE	A16/A24	00_2
MANUFACTURER ID	$FA0_{16}$	TBD
REQUIRED MEMORY	128 kbytes	TBD
MODEL CODE	x074	TBD

VXIbus Compatibility	Type
DEVICE CLASS	Extended-Register-Based
DEVICE TYPE	Servant-only
LOGICAL ADDRESS SELECTION	Static Switch Configuration
INTERRUPTER	Programmable